A SECOND STELLAR COLOR LOCUS: A BRIDGE FROM WHITE DWARFS TO M STARS

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ABSTRACT

We report the discovery of a locus of stars in the SDSS $g-r$ vs. $u-g$ color-color diagram that connects the colors of white dwarfs and M dwarfs. While its contrast with respect to the main stellar locus is only ~1:2300, this previously unrecognized feature includes 863 stars from the SDSS Data Release 1. The position and shape of the feature are in good agreement with predictions of a simple binary star model that consists of a white dwarf and an M dwarf, with the components' luminosity ratio controlling the position along this binary system locus. SDSS DR1 spectra for 47 of these objects strongly support this model. The absolute magnitude–color distribution inferred for the white dwarf component is in good agreement with the models of Bergeron et al. (1995).

1. INTRODUCTION

Modern large-scale accurate photometric surveys offer an unprecedented view of stellar populations. Here we discuss a population of unresolved binary stars which account for fewer than 10^{-3} of stars detected by the Sloan Digital Sky Survey (York et al. 2000). Despite this low occurance frequency, the sample presented here is sufficiently large (~1000 stars) to characterize their broad-band optical properties.

1.1. *Sloan Digital Sky Survey*

The Sloan Digital Sky Survey (SDSS; Abazajian et al. 2003, and references therein) is revolutionizing stellar astronomy by providing homogeneous and deep ($r < 22.5$) photometry in five passbands (u, g, r, i, and z; Fukugita et al. 1996, Gunn et al. 1998, Hogg et al. 2001, Smith et al. 2002), accurate to 0.02 mag (Ivezić et al. 2003). Ultimately, up to 10,000 $\deg^2$ of sky in the Northern Galactic Cap will be surveyed. The survey sky coverage will result in photometric measurements for over 100 million stars and a similar number of galaxies. Astrometric positions are accurate to better than 0.1 arcsec per coordinate (rms) for point sources with $r < 20.5^m$ (Pier et al. 2003), and the morphological information from the images allows robust star-galaxy separation to $r \sim 21.5^m$ (Lupton et al. 2003).

Here we report the results of a color-based search for binary stars in the recent SDSS Data Release 1 (see www.sdss.org), which includes 53 million unique objects detected in 2099 $\deg^2$ of sky.

1.2. *The Stellar Locus in the SDSS Photometric System*

The effective temperature is the dominant parameter that determines the position of the majority of stars in optical color-color diagrams constructed with broad-band filters (Lenz et al. 1998, and references therein). The effective temperature range results in a well-defined stellar locus in color-color diagrams (for more details see Finlator et al. 2000, and references therein).

2. THE LOCUS OF BINARY STARS

An unresolved binary star may have colors that place it either inside or outside the locus. If the luminosity of one star is much greater than that of the other, the more luminous star determines the system colors. However, even if the luminosities are comparable, the system color may still fall close to the locus of single stars in color-color diagrams where the locus resembles a straight line (e.g. the $i - z$ vs. $r - i$ diagram). Thus, to select unresolved binary systems by their colors, the most promising diagrams are those where the locus is curved, such as the $g - r$ vs. $u - g$ and $r - i$ vs. $g - r$ color-color diagrams. The curvature in these diagrams is the result of saturation of the $u - g$ and $g - r$ colors due to the strong molecular absorption bands which first appear at type ~M0.

Figure 1 shows the $g - r$ vs. $u - g$ color-color diagram for ~1.99 million stars from the public SDSS Data Release 1 (DR1) database with $u < 20.5$. This magnitude limit ensures that the accuracy of the u magnitudes is better than 0.1 mag (for $u < 18$, the photometric accuracy is 0.02 mag, Ivezić et al. 2003). The most prominent feature is the main stellar locus. Due to the large number of stars in

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DR1, we are able to demonstrate the existence of a second stellar locus, clearly visible just above the main stellar locus. The number of stars in this, previously unreported feature, is a factor of ∼2,300 smaller than in the main locus (using color cuts listed in the next Section). Thus, accurate multi-band photometry (u band in particular) for a sufficiently large number of stars was required to detect such a low-contrast feature.

The second stellar locus is consistent with binary systems than include an M dwarf and a white dwarf. We demonstrate that this simple model provides a satisfactory explanation for the position of the second stellar locus, hereafter the "bridge" (from M dwarfs to white dwarfs). We also show that the available SDSS spectra for a subsample of bridge stars support this interpretation.
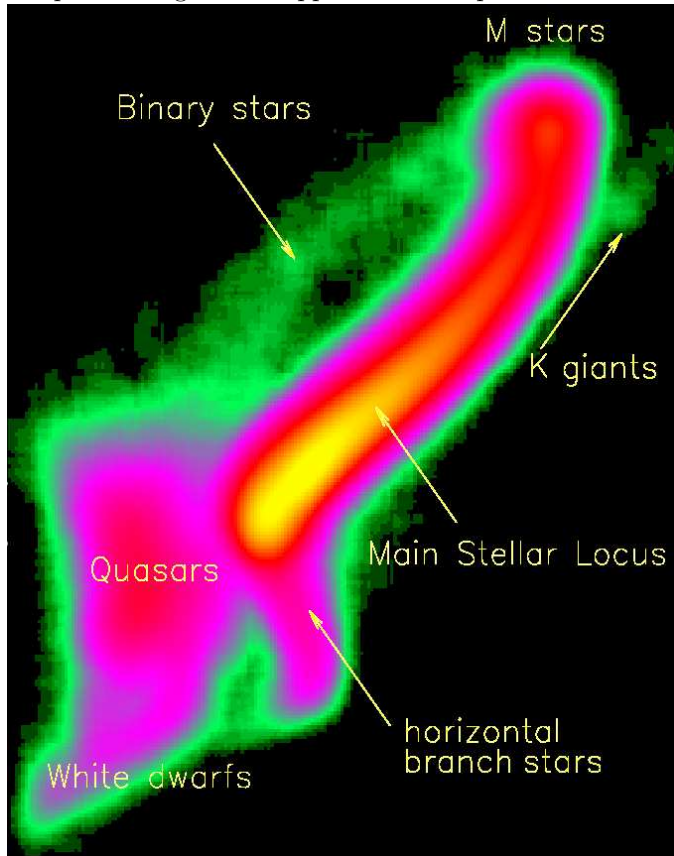

FIG. 1.— The number density, displayed on a logarithmic scale, of ∼1.99 million stars with $u < 20.5$ from SDSS Data Release 1 in the $g - r$ vs. $u - g$ color-color diagram (increasing from green to red to yellow; the color axes increase towards upper right and the color ranges are -1 to 3, and -1 to 2, for $u - g$ and $g - r$, respectively). The most prominent features are the main stellar locus and the clump of low-redshift quasars, as marked. Other notable features include the locus of white dwarfs, horizontal branch stars (also including blue stragglers and RR Lyrae stars), and low-metallicity K giants. The fainter feature colored green, above and to the left of the main locus, is the locus of ∼1,000 binary stars. The properties of this locus are consistent with a distribution of M dwarf – white dwarf pairs with varying luminosity ratio. The root-mean-scatter of stars about this locus is only ∼0.1 mag.

3. M DWARF – WHITE DWARF MODEL

The bridge of stars in the $g - r$ vs. $u - g$ color-color diagram appears to connect the positions of M stars and hot blue stars, with MK spectral type around B. In order to produce a locus of stars that is not coincident with the main stellar locus, the luminosities of the two components

must be comparable. The possibilities are an M dwarf – white dwarf pair, or an M giant – blue giant/supergiant pair. The latter systems cannot dominate the sample because the sky density of the selected stars (0.40 deg^{-2}) is too high, given the faint magnitudes and high latitudes probed by SDSS (see Majewski et al. 2004 for a nearly complete census of M giants in the Galaxy).

We generate model colors for binary systems by assuming SDSS colors for single M dwarf and white dwarf stars, and parametrize the system colors by the luminosity ratio of the two components (in practice, we use the r band flux fractions). For the M dwarf we adopt $u - g = 2.6$, $g - r = 1.4$, $r - i = 2(i - z)$, and $i - z = 0.3$ to 0.75, with a step of 0.05, and for the white dwarf $u - g = 0.2$, $g - r = -0.2$, $r - i = 0$, $i - z = 0$. For more details about M dwarfs and white dwarfs discovered by SDSS see Hawley et al. (2002), Harris et al. (2003), Raymond et al. (2003) and Kleinman et al. (2004). The model predictions are compared to the data in Figure 2, where the dots represent 863 "DR1 bridge stars", selected by requiring $u < 20.5$, $u - g < 2$, $g - r > 0.3$, $r - i > 0.7$, and that processing flags BRIGHT, SATUR and BLENDED are not set (the flag requirement selects unique unsaturated objects, see Abazajian et al. 2003). We corrected all colors for the interstellar reddening using the maps from Schlegel, Finkbeiner & Davis (1998); typical corrections at the high galactic latitudes considered here are < 0.05 mag.
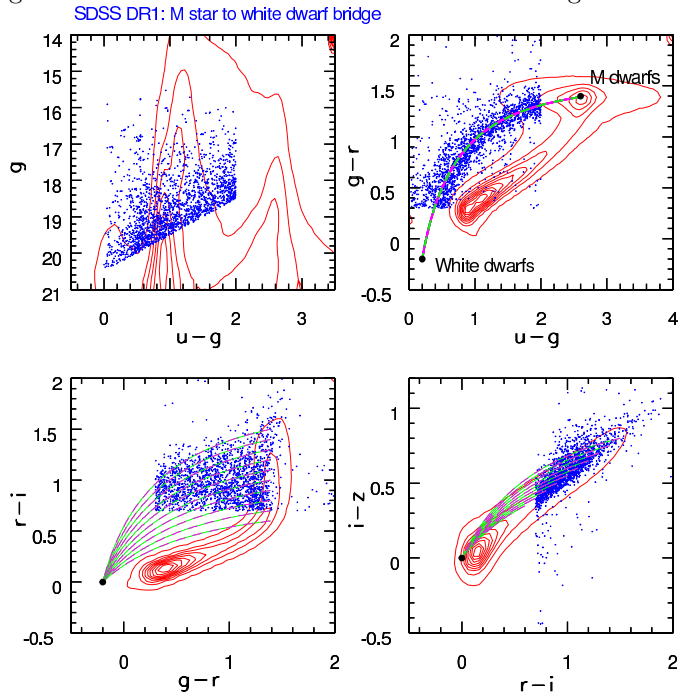

FIG. 2.— The comparison of a simple M dwarf – white dwarf pair model with the data. A representative distribution of all stars is shown by linearly spaced isopleths. 863 stars from SDSS Data Release 1 selected by requiring $u < 20.5, u - g < 2, g - r > 0.3$ and $r - i > 0.7$ are shown by dots. The model predictions are shown by lines, where each line corresponds to different $r - i$ and $i - z$ colors assumed for the M dwarf. The position along the line depends on the luminosity ratio of the two components. There is only one line in the $g - r$ vs. $u - g$ diagram (top right) because all M dwarfs have practically the same $u - g$ and $g - r$ colors (Finlator et al. 2000, Hawley et al. 2002). The observed data scatter around this line is presumably due to a distribution of white dwarf colors, photometric errors, and sample contamination by other types of source.

The agreement between this simple binary star model and the data is satisfactory. In particular, the model track closely follows the distribution of bridge stars in the $g - r$ vs. $u - g$ color-color diagram, and reproduces the observed range of colors in other diagrams. A noteworthy point is that the implied contribution of the white dwarf to the total r band flux is at most 50% for practically all stars from the "DR1 bridge" sample (for equal r band flux contributions, the model predicts $u - g = 0.40$ and $g - r = 0.33$).
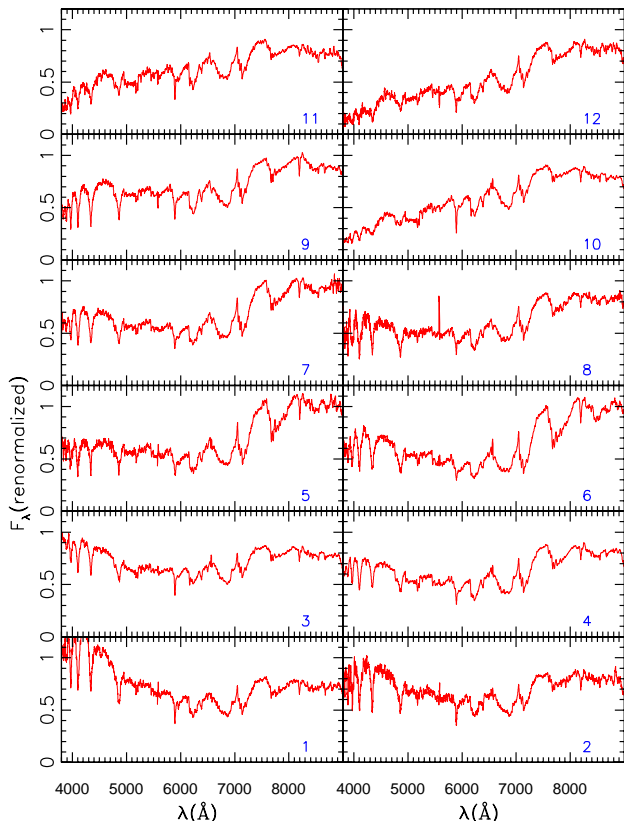

FIG. 3.— SDSS spectra for a subsample of stars whose SDSS colors are consistent with an M dwarf – white dwarf binary system. In all the shown systems the red half of the spectrum is typical of an M dwarf, while the blue half is consistent with a white dwarf spectrum. Spectra are approximately ordered by the M dwarf to white dwarf flux ratio in the r band. Note prominent Hα emission for stars 3 and 6. The feature at $\sim$5,577Å is due to the night sky.

4. SDSS SPECTRA

While the close agreement between the data and model predictions supports the hypothesis that the bridge stars are dominated by M dwarf – white dwarf pairs, further confirmation can be gained by examining the available SDSS spectra. Stars are selected by various criteria for SDSS spectroscopic observations, and we postpone a detailed analysis of the selection statistics to a forthcoming publication. Here we simply report the results of a visual examination of 47 "bridge" stars from the DR1 sample for which SDSS spectra are available. The spectra are obtained through 3″ fibers, and span the wavelength range 3800–9200Å, with a spectral resolution of $\lambda/\Delta\lambda \sim 1800$.

Out of 863 stars in the sample, spectra are available for 47. The visual inspection of spectra indicates that 45 are consistent with an M dwarf–white dwarf interpretation

(the remaining 2 are G stars; both are close to the color-selection boundary, and one belongs to a complex blended source). We display a representative sample of spectra in Figure 3. A preliminary comparison with the M dwarf spectral sequence (Hawley et al. 2002) indicates that M dwarfs in the binary systems discussed here are dominated by types M5 and earlier, as is the case for single M dwarfs in this magnitude-limited sample. This conclusion is also supported by the distribution of their $r - i$ and $i - z$ colors (the median $r - i$ color is $\sim$1.0, see the lower left panel in Figure 2).

We visually compared all spectra to the atlas of white dwarf spectra by Wesemael et al. (1993). About half belong to the DA class, and about one third can be tentatively classified as subdwarfs. Other classes that are probably present in the sample include DB, DZ and DQ. We note that SDSS spectra are of sufficient quality to allow determination of the white dwarf temperature and the M dwarf chromospheric activity (via Hα emission), as demonstrated by Raymond et al. (2003). Such an analysis will be presented in a forthcoming publication.
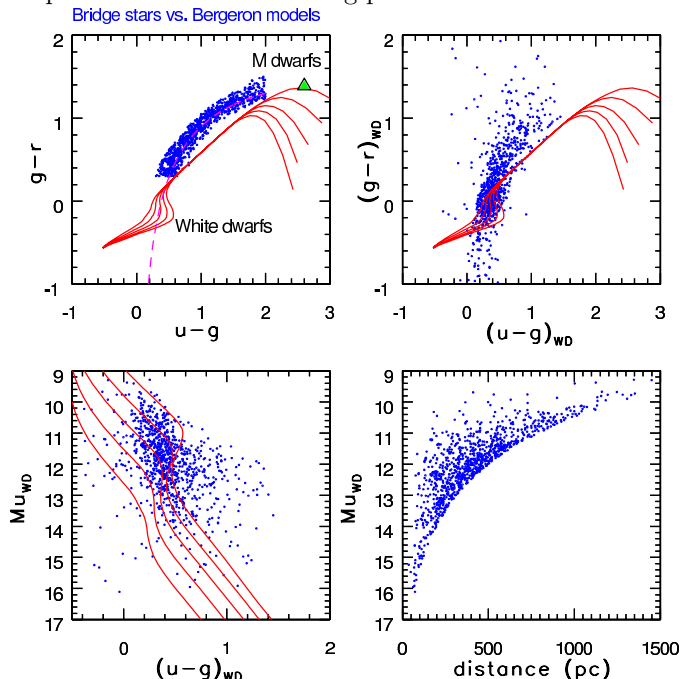

FIG. 4.— The comparison of data with Bergeron et al. (1995) white dwarf models. The symbols in the top left panel display the $g - r$ vs. $u - g$ color distribution for bridge stars, and the lines are white dwarf models with log(g)=(7, 7.5, 8, 8.5, 9). For a given $g - r$ color, the models with larger log(g) have bluer $u - g$ color (the temperature range is from 1500 K to 10^5 K). The top right panel is analogous to the top left panel, except that the symbols show the color distribution for the white dwarf component. The bottom left panel compares the color-magnitude distribution for the white dwarf component with the model predictions (for a given $u - g$ color, log(g) decreases with the luminosity). The white dwarf absolute magnitude – distance distribution is shown in the bottom right panel.

5. COMPARISON WITH WHITE DWARF MODELS

The models discussed in Section 3 indicate that the white dwarf contribution to the i and z band fluxes is practically negligible. Hence, the absolute i band magnitude for the M dwarf component, M_i, and therefore distances, can be obtained using the M_i vs. $i - z$ color-magnitude relation from Hawley et al. (2002). With an

estimate for distance, the absolute u band magnitude for the white dwarf component can be determined, and compared to model cooling curves. Two additional parameters that can be derived from the data are the $u - g$ color for the white dwarf component, and the components' r band flux (or luminosity) ratio. In this analysis, we further constrain the sources to be very close (0.15 mag) to the "bridge" by requiring $P_2 < 0.5 \, P_1^2 + 0.15$ and $P_2 > 0.2 \, P_1^2 - 0.15$, where $P_1 = -0.5 \, (u - g) - (g - r) + 1.5$ and $P_2 = 0.7 \, (u - g) - (g - r) + 0.2$.

Using this approach we find a median $M_i \sim 9$ for the M dwarf component, with a root-mean-scatter of 1 mag. The corresponding median distance is $\sim$400 pc. The derived white dwarf parameters are compared to models by Bergeron et al. (1995) in Fig. 4. As shown in the top right panel, the estimated white dwarf colors agree well with the model predictions. Similarly, fairly good agreement is obtained for the luminosity–color distribution displayed in the bottom left panel. Models with $7 < \log(g) < 8.5$ bracket the majority of data points, in agreement with the analysis of isolated white dwarfs with SDSS spectra (Kleinman et al. 2004). About 20% of data points have $u - g$ color, for a given absolute magnitude, too red by about 0.5 mag (or equivalently, for a given $u - g$ color, absolute magnitude is too bright by $\sim$2 mag). This discrepancy could be due to sample contamination by other types of source.

The white dwarf absolute magnitude – distance distribution is shown in the bottom right panel. Since the sample presented here is an unbiased, u flux-limited sample (with the adopted u magnitude limit, the other four SDSS magnitudes for all stars in the sample are comfortably brighter than the corresponding SDSS completeness limits), it would be straightforward to determine the white dwarf luminosity function and the number density (assuming that the components are not strongly interacting). However, the unresolved binary stars discussed here are heavily biased towards systems with components that have similar luminosities, and it is not trivial to account for this effect. Such a detailed analysis of M dwarf and white dwarf luminosity functions in unresolved binary systems will be presented in a forthcoming publication.

6. CONCLUSIONS

The accurate multi-band SDSS photometry for a large number of stars allowed detection of a new feature in the broad-band optical color-color diagrams: a "bridge" of stars, well-separated from the main stellar locus, connects the positions of M dwarfs and white dwarfs. The bridge characteristics are consistent with a binary system than includes an M dwarf and a white dwarf, with the system's position on the bridge determined by the components' luminosity ratio. This conclusion is strongly supported by SDSS spectra for 47 such systems.

The distance to these systems can be estimated in a straightforward way because a photometric parallax relation for M dwarfs can be applied to i and z band measurements, where the contribution from the white dwarf is negligible. With a known system distance, the white dwarf luminosity-color distributions can be determined and compared to models. We find that models by Bergeron et al. (1995) are in good agreement with the data.

This work analyzed only about a quarter of the data that will be obtained by the SDSS. Thus, the color selection method presented here will eventually yield $\sim$4,000 unresolved M dwarf– white dwarf binary systems.

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